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APPENDIX D: VERTICAL STRATIFICATION AND THE PYCNOCLINE

The *pycnocline* has a functional role in defining designated use boundaries. The designated use boundaries are set, taking into account the types and needs of the living resources that inhabit different parts of the Bay, as well as the bathymetry, hydrology, physical features and natural stratification of the Bay waters as described in Section 4.

Vertical stratification is foremost among the physical factors affecting dissolved oxygen concentrations in some parts of Chesapeake Bay and its tidal tributaries. Stratification arises from differences in water density within the water column due to vertical differences in salinity and temperature of the source waters feeding into Chesapeake Bay tidal waters and the extent of their vertical mixing. Generally, the water coming into Chesapeake Bay and its tidal tributaries from the land via the tributaries is fresh and less dense than the saline water from the ocean. Temperature affects density such that the colder water is, the more dense it becomes and vice versa. The simple model is that the less dense fresh water moves seaward over the layer of more dense seawater moving from the mouth northward. Depending on the extent and nature of the mixing of the two, the vertical density profile will be a smooth gradient (**Exhibit D-1**) or sharp stepwise function (**Exhibit D-2**) or something in between. To the extent that the two (or more) layers remain self-contained and poorly mixed, the waters are stratified. If the density discontinuity is great enough to prevent mixing of the layers and constitutes a vertical barrier to diffusion of dissolved oxygen, then a pycnocline is said to exist. In places where there are multiple inflows and complex circulation patterns, there may be multiple pycnoclines. The middle mainstem Chesapeake Bay region between the Chesapeake Bay Bridge and just below the Potomac River is such a region.

When physical features like channels, holes and sills inhibit lateral exchange of waters and a pycnocline inhibits vertical exchange, oxygen that is consumed in biological respiration or other oxygen-consuming processes in the imprisoned subpycnocline waters can not be replenished. When there is no barrier to lateral exchange, the effect of the pycnocline on lower layer oxygen levels may be ameliorated. For this reason, the extent of isolation caused by a pycnocline, as well as the frequency of formation and the depth of the pycnocline when present are factors to be considered in defining designated use boundaries.

CALCULATING PYCNOCLINE DEPTH

The Chesapeake Bay Program Water Quality Monitoring Program collects vertical profiles of temperature, salinity and conductivity measurements (among other parameters) at 1 to 2 meter intervals at each of its sampling stations. From these measurements, there are at least two approaches for determining a pycnocline:

1) Construct a vertical density (sigma_t) profile from which a pycnocline can be determined by doing the following sequence of calculations:

sigo = –0.069+((1.47808*((salinity-0.03)/1.805))
–(0.00157*(((salinity–0.03)/1.805)**2))
+(0.0000398*(((salinity–0.03)/1.805)**3)));

tsum = (–1*(((tempc-3.98)**2)/503.57)) * ((tempc+283)/(tempc+67.26));

sa = (10**–3)*tempc)*(4.7867-(0.098185*tempc)+(0.0010843*(tempc**2)));

sb = ((10**–6)*tempc)*(18.030–(0.8164*tempc)+(0.01667*(tempc**2)));

Sigma_t = tsum+((sigo+0.1324)*(1-sa+sb*(sigo–0.1324))); or

2) Calculate a 'working' pycnocline depth using vertical differences in conductivity. The following is the Chesapeake Bay Monitoring Program field method and the standard for determining the presence of a pycnocline and, if one or more exist, the depth of the upper and lower boundary.

   a) Find the average rate of change from surface to bottom: i.e., subtract surface conductivity from bottom conductivity and divide by the depth.

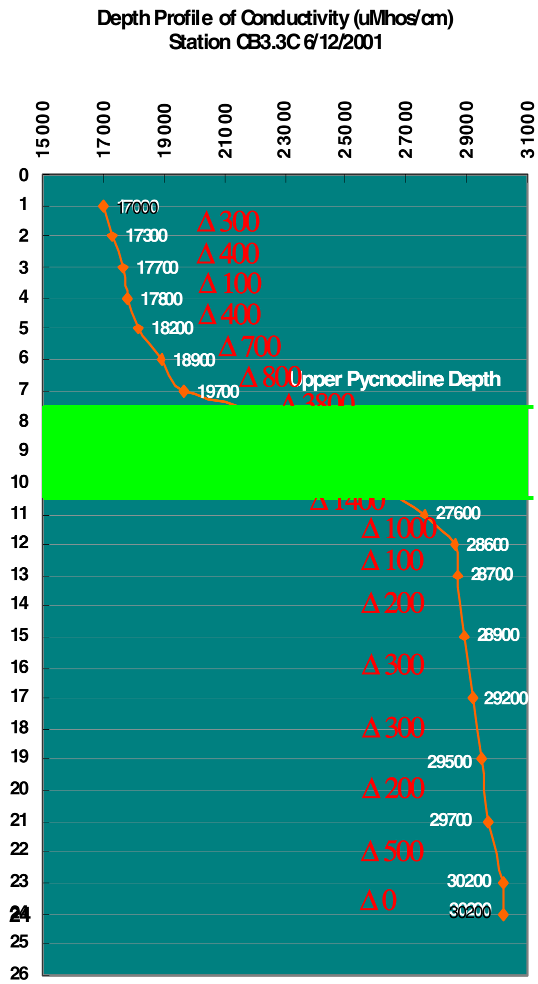
   b) Multiply the average rate of change by 2. This is called the *threshold.*

   c) If the threshold is less than 500, then it is determined that no pycnocline exists at the site.

   d) It the threshold is 500 or greater, then each interval from surface to bottom is checked to determine if the difference from one meter to the next is greater than or equal to the threshold. The upper pycnocline is defined as the first encounter of a difference that exceeds the threshold and the upper pycnocline depth is set at one-half the depth interval distance. For example, if the threshold is first exceeded between 4 and 5 m, then the pycnocline is set at 4.5 m.

   e) Then the process is reversed and each interval from bottom to surface is checked. If the threshold is exceeded at a depth more than 1.5 m from the upper pycnocline, then a second pycnocline is said to exist and the lower pycnocline depth is set at one-half the depth interval distance, as before.

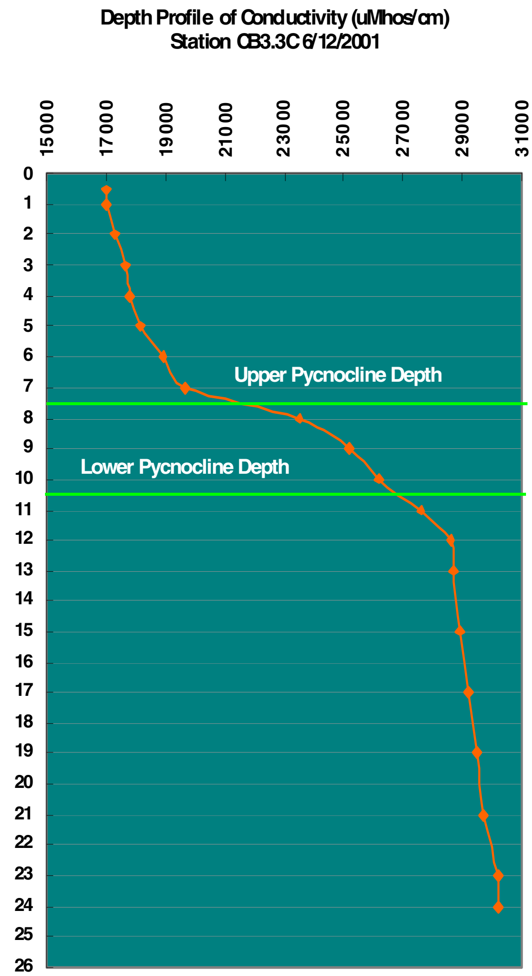
Exhibit D-3 provides some statistics on the frequency of occurrence, depth of pycnoclines, and the distance between upper and lower pycnoclines in spring and summer at locations throughout the Bay and tributaries. The statistics are for each Chesapeake Bay Water Quality Monitoring Program station over the history of the program 1985–2000. (See the Chesapeake Bay Program website at http://ww.chesapeakebay.net for a map of these stations.)



x 2 = 1100

- Threshold = twice the mean conductivity change between depths
- Upper Pycnocline depth located by moving from surface to bottom and finding Δ cond > threshold
- Lower Pycnocline depth located by moving from bottom to surface and finding Δ cond > threshold

Exhibit D-1: Smooth Gradient Depth Profile of Conductivity



Conditions

- Upper Pycnocline Depth must be >1 m
- Threshold must exceed 500
- If threshold is not exceeded then no pycnocline
- Difference between upper and lower pycnocline depths must be > 1m

Exhibit D-2: Sharp Stepwise Function Profile of Conductivity

Exhibit D-3: Median Station Pycnocline Depths and Percent Occurrence: 1985–2000

Segment	Station	Spring (March–May)						Summer (July–September)					
		Station Depth	Upper Depth	Pct Upper	Lower Depth	Pct Lower	Interpyc Depth	Station Depth	Upper Depth	Pct Upper	Lower Depth	Pct Lower	Interpyc Depth
CB1TF	CB1.1	6	.	0	.	0	.	6	.	0	.	0	.
CB1TF	CB2.1	6	3.5	1	.	0	.	6	2.5	10	.	0	.
CB2OH	CB2.2	12	7.5	45	10.5	12	2.5	12	6.5	42	10.5	8	4.0
CB2OH	CB3.1	13	4.5	90	7.5	30	3.0	13	4.5	84	7.5	33	2.0
CB3MH	CB3.2	12	5.5	94	5.5	23	2.0	12	5.5	69	7.0	21	3.0
CB3MH	CB3.3C	25	4.5	99	10.5	88	5.0	24	6.5	91	11.5	78	6.0
CB3MH	CB3.3E	9	5.5	57	6.5	6	2.0	8	5.0	31	5.5	1	2.0
CB3MH	CB3.3W	9	6.0	66	7.5	7	2.0	9	6.5	58	7.5	2	2.3
CB4MH	CB4.1C	33	5.5	96	13.5	93	8.0	32	6.5	79	14.5	74	7.0
CB4MH	CB4.1E	24	6.5	94	12.5	79	6.0	24	7.5	66	12.5	54	5.0
CB4MH	CB4.1W	9	7.0	76	7.5	6	1.5	9	6.5	34	7.5	1	2.0
CB4MH	CB4.2C	28	7.5	96	13.5	90	6.0	27	8.5	86	14.5	81	6.0
CB4MH	CB4.2E	9	6.0	43	8.0	5	2.5	9	6.0	42	8.0	2	2.0
CB4MH	CB4.2W	10	6.0	39	7.5	11	2.0	9	6.0	22	7.5	6	1.5
CB4MH	CB4.3C	27	7.5	98	12.5	92	5.0	27	9.5	87	14.5	79	5.0
CB4MH	CB4.3E	23	6.5	95	13.5	88	5.0	22	10.5	86	15.5	79	4.0
CB4MH	CB4.3W	10	6.0	32	8.0	6	2.0	10	7.5	22	7.5	2	4.0
CB4MH	CB4.4	30	8.0	89	14.5	86	7.0	30	9.5	86	14.5	83	6.0
CB5MH	CB5.1	35	7.0	73	15.5	66	8.5	34	7.5	78	13.5	72	5.5
CB5MH	CB5.2	31	8.5	76	14.5	74	6.0	30	9.5	83	14.5	79	6.0
CB5MH	CB5.3	27	8.5	83	12.5	71	5.0	27	7.5	86	11.5	72	4.0

Exhibit D-3: Median Station Pycnocline Depths and Percent Occurrence: 1985–2000

Segment	Station	Spring (March–May)						Summer (July–September)					
		Station Depth	Upper Depth	Pct Upper	Lower Depth	Pct Lower	Interpyc Depth	Station Depth	Upper Depth	Pct Upper	Lower Depth	Pct Lower	Interpyc Depth
CB5MH	CB5.4	32	6.0	42	14.5	42	8.0	32	6.5	60	12.5	60	6.0
CB5MH	CB5.4W	5	3.0	12	.	0	.		5	3.5	19	.	0
CB5MH	CB5.5	19	7.5	61	12.5	47	5.0	19	5.5	74	11.5	57	5.0
CB6PH	CB6.1	13	7.5	80	8.5	30	3.0	13	7.5	91	9.5	33	2.0
CB6PH	CB6.2	11	6.5	80	7.5	20	2.0	11	6.5	91	7.5	11	2.0
CB6PH	CB6.3	12	5.5	75	7.5	30	2.0	13	5.5	91	7.5	26	2.0
CB6PH	CB6.4	10	6.5	80	8.0	17	3.0	10	5.0	74	7.0	7	2.0
CB7PH	CB7.1	25	5.5	31	8.5	25	5.0	25	5.5	28	8.5	23	4.0
CB7PH	CB7.1N	31	5.5	6	7.5	4	5.0	31	8.5	9	14.5	8	5.0
CB7PH	CB7.1S	16	5.5	66	8.5	31	3.0	16	5.5	76	7.5	40	3.0
CB7PH	CB7.2	22	4.0	77	8.5	61	5.0	22	4.5	84	7.5	67	3.0
CB7PH	CB7.2E	13	3.5	42	6.5	10	3.0	13	3.5	58	6.5	16	2.0
CB7PH	CB7.3	14	4.5	81	8.5	50	3.0	14	3.8	79	8.0	35	3.0
CB7PH	CB7.3E	18	4.0	66	12.5	37	6.0	18	3.5	56	13.5	27	5.0
CB7PH	CB7.4N	13	3.0	41	10.0	23	5.0	13	3.5	23	7.9	5	3.0
CB7PH	EE3.5	28	8.5	4	14.5	4	11.0	27	4.5	9	11.5	8	7.0
CB8PH	CB7.4	14	4.5	65	7.0	26	3.0	14	2.5	63	5.5	24	3.0
CB8PH	CB8.1	10	5.5	77	7.5	20	2.0	9	5.5	78	7.5	16	2.0
CB8PH	CB8.1E	18	5.5	84	9.5	46	2.8	18	5.5	85	8.0	38	3.0
NORTF	ET1.1	3	.	0	.	0	.	3	.	0	.	0	.
C&DOH	ET2.1	13	.	0	.	0	.	13	.	0	.	0	.

Exhibit D-3: Median Station Pycnocline Depths and Percent Occurrence: 1985–2000

Segment	Station	Spring (March–May)						Summer (July–September)					
		Station Depth	Upper Depth	Pct Upper	Lower Depth	Pct Lower	Interpyc Depth	Station Depth	Upper Depth	Pct Upper	Lower Depth	Pct Lower	Interpyc Depth
BOHOH	ET2.2	3	2.3	3	.	0	.	3	.	0	.	0	.
ELKOH	ET2.3	13	.	0	.	0	.	13	.	0	.	0	.
SASOH	ET3.1	5	.	0	.	0	.	6	2.5	2	.	0	.
CHSOH	ET4.1	5	.	0	.	0	.	5	.	0	.	0	.
CHSMH	ET4.2	14	7.5	70	8.5	33	3.0	14	7.5	29	9.5	15	3.0
CHSMH	XGG8251	6	5.5	2	.	0	.	6	.	0	.	0	.
EASMH	EE1.1	13	8.5	59	10.5	23	2.0	12	8.5	50	10.5	22	2.7
CHOOH	ET5.1	6	.	0	.	0	.	6	.	0	.	0	.
CHOMH2	ET5.2	12	4.5	26	6.5	4	2.0	12	4.0	16	7.0	4	3.5
CHOMH1	EE2.1	8	5.5	24	6.5	3	1.5	8	5.5	22	.	0	.
LCHMH	EE2.2	13	5.5	51	8.5	14	2.0	13	5.5	43	8.5	18	2.0
FSBMH	EE3.0	7	3.5	7	.	0	.	7	.	0	.	0	.
NANTF	ET6.1	5	.	0	.	0	.	5	.	0	.	0	.
NANMH	ET6.2	4	2.5	14	.	0	.	4	2.3	3	.	0	.
WICMH	ET7.1	7	4.1	5	.	0	.	8	.	0	.	0	.
MANMH	ET8.1	5	2.5	12	.	0	.	5	.	0	.	0	.
BIGMH	ET9.1	5	.	0	.	0	.	5	.	0	.	0	.
POCTF	ET10.1	6	.	0	.	0	.	5	.	0	.	0	.
POCMH	EE3.3	4	2.4	13	.	0	.	4	2.5	4	.	0	.
POCMH	EE3.4	5	2.5	7	.	0	.	5	2.5	5	.	0	.
TANMH	EE3.1	13	4.0	21	9.5	9	3.7	13	3.5	1	.	0	.

Exhibit D-3: Median Station Pycnocline Depths and Percent Occurrence: 1985–2000

Segment	Station	Spring (March–May)						Summer (July–September)					
		Station Depth	Upper Depth	Pct Upper	Lower Depth	Pct Lower	Interpyc Depth	Station Depth	Upper Depth	Pct Upper	Lower Depth	Pct Lower	Interpyc Depth
TANMH	EE3.2	27	12.5	4	21.5	4	12.0	27	8.0	4	10.8	3	5.0
BSHOH	WT1.1	3	.	0	.	0	.	3	.	0	.	0	.
GUNOH	WT2.1	2	.	0	.	0	.	2	.	0	.	0	.
MIDOH	WT3.1	3	2.1	3	.	0	.	3	2.3	7	.	0	.
BACOH	WT4.1	2	.	0	.	0	.	.	.	0	.	0	.
PATMH	WT5.1	15	5.5	98	10.5	58	4.0	15	6.5	90	11.5	59	3.0
MAGMH	WT6.1	6	4.0	33	.	0	.	6	3.5	24	.	0	.
SEVMH	WT7.1	9	4.0	39	6.5	7	2.0	9	4.5	30	.	0	.
SOUMH	WT8.1	9	3.5	38	5.5	7	2.0	9	2.5	23	.	0	.
RHDMH	WT8.2	3	2.2	6	.	0	.	3	1.9	3	.	0	.
WSTMH	WT8.3	3	2.3	12	.	0	.	3	2.3	10	.	0	.
PAXTF	TF1.5	11	.	0	.	0	.	11	.	0	.	0	.
WBRTF		.	.	0	.	0	.	.	.	0	.	0	.
PAXOH	TF1.6	6	.	0	.	0	.	6	.	0	.	0	.
PAXOH	TF1.7	3	.	0	.	0	.	3	.	0	.	0	.
PAXMH	LE1.1	12	4.6	32	.	0	.	12	4.5	14	.	0	.
PAXMH	LE1.2	17	4.6	12	13.5	1	3.0	17	7.5	11	13.2	2	5.6
PAXMH	LE1.3	24	7.5	3	.	0	.	24	10.5	3	13.5	1	3.0
PAXMH	LE1.4	15	10.7	23	13.1	7	2.5	15	13.0	18	13.3	2	2.8
PAXMH	RET1.1	11	4.6	10	9.6	1	5.0	11	6.1	7	.	0	.
POTTF	TF2.1	19	.	0	.	0	.	19	.	0	.	0	.

Exhibit D-3: Median Station Pycnocline Depths and Percent Occurrence: 1985–2000

Segment	Station	Spring (March–May)						Summer (July–September)					
		Station Depth	Upper Depth	Pct Upper	Lower Depth	Pct Lower	Interpyc Depth	Station Depth	Upper Depth	Pct Upper	Lower Depth	Pct Lower	Interpyc Depth
POTTF	TF2.2	8	.	0	.	0	.	8	.	0	.	0	.
POTTF	TF2.3	13	.	0	.	0	.	13	.	0	.	0	.
POTTF	TF2.4	9	.	0	.	0	.	9	6.3	1	.	0	.
PISTF	XFB1986	2	.	0	.	0	.	2	.	0	.	0	.
MATTF	MAT0016	7	.	0	.	0	.	7	.	0	.	0	.
POTOH	RET2.1	8	5.4	4	.	0	.	7	5.3	1	.	0	.
POTOH	RET2.2	10	5.8	8	.	0	.	10	5.8	7	7.3	1	1.6
POTOH	RET2.3	9	6.6	7	.	0	.	9	.	0	.	0	.
POTMH	LE2.2	11	5.5	92	7.5	29	3.0	12	6.5	84	8.5	31	2.0
POTMH	LE2.3	20	7.5	60	14.5	45	5.0	20	8.5	63	12.5	48	4.0
POTMH	RET2.4	16	5.5	48	10.0	27	3.9	16	4.5	24	9.5	15	4.0
RPPTF	TF3.1A	3	.	0	.	0	.	3	.	0	.	0	.
RPPTF	TF3.1B	3	.	0	.	0	.	3	.	0	.	0	.
RPPTF	TF3.1C	6	.	0	.	0	.	.	.	0	.	0	.
RPPTF	TF3.1D	3	.	0	.	0	.	3	.	0	.	0	.
RPPTF	TF3.1E	3	.	0	.	0	.	3	.	0	.	0	.
RPPTF	TF3.2	6	.	0	.	0	.	7	.	0	.	0	.
RPPTF	TF3.2A	5	.	0	.	0	.	5	.	0	.	0	.
RPPOH	TF3.3	7	.	0	.	0	.	7	4.0	1	7.5	1	3.5
RPPMH	LE3.1	6	5.5	43	.	0	.	6	5.5	23	.	0	.
RPPMH	LE3.2	14	6.0	40	6.0	10	2.0	14	6.0	29	10.0	7	2.0

Exhibit D-3: Median Station Pycnocline Depths and Percent Occurrence: 1985–2000

Segment	Station	Spring (March–May)						Summer (July–September)					
		Station Depth	Upper Depth	Pct Upper	Lower Depth	Pct Lower	Interpyc Depth	Station Depth	Upper Depth	Pct Upper	Lower Depth	Pct Lower	Interpyc Depth
RPPMH	LE3.4	11	8.0	29	10.0	1	2.0	11	8.0	26	9.8	6	2.0
RPPMH	LE3.6	10	6.0	19	8.0	1	2.0	10	6.0	30	8.0	7	2.0
RPPMH	RET3.1	6	4.0	10	.	0	.	6	.	0	.	0	.
RPPMH	RET3.2	4	3.5	14	.	0	.	4	3.5	12	.	0	.
CRRMH	LE3.3	5	4.0	4	.	0	.	5	4.0	1	.	0	.
PIAMH	LE3.7	7	3.5	6	.	0	.	7	4.5	9	4.5	1	2.0
MPNTF	TF4.4	3	.	0	.	0	.	3	.	0	.	0	.
MPNTF	TF4.4A	7	.	0	.	0	.	6	.	0	.	0	.
MPNOH	RET4.2	12	.	0	.	0	.	12	.	0	.	0	.
PMKTF	TF4.1A	5	.	0	.	0	.	6	.	0	.	0	.
PMKTF	TF4.2	7	.	0	.	0	.	7	.	0	.	0	.
PMKOH	RET4.1	5	4.0	2	.	0	.	5	.	0	.	0	.
YRKMH	LE4.1	8	6.0	35	6.0	2	2.0	8	6.0	16	.	0	.
YRKMH	RET4.3	5	4.0	11	.	0	.	5	5.5	1	.	0	.
YRKPH	LE4.2	13	4.0	27	7.0	3	2.0	13	6.0	14	8.0	5	2.0
YRKPH	LE4.3	16	10.0	32	12.0	8	2.0	15	8.0	21	10.0	9	2.0
MOBPH	WE4.1	6	3.5	7	.	0	.	6	3.5	19	.	0	.
MOBPH	WE4.2	13	8.5	46	10.5	23	3.0	14	8.5	31	10.5	16	3.0
MOBPH	WE4.3	6	4.5	4	.	0	.	6	3.5	4	.	0	.
MOBPH	WE4.4	8	.	0	.	0	.	8	.	0	.	0	.
JMSTF	TF5.2	7	.	0	.	0	.	.	.	0	.	0	.

Exhibit D-3: Median Station Pycnocline Depths and Percent Occurrence: 1985–2000

Segment	Station	Spring (March–May)						Summer (July–September)					
		Station Depth	Upper Depth	Pct Upper	Lower Depth	Pct Lower	Interpyc Depth	Station Depth	Upper Depth	Pct Upper	Lower Depth	Pct Lower	Interpyc Depth
JMSTF	TF5.2A	8	.	0	.	0	.	8	.	0	.	0	.
JMSTF	TF5.3	11	.	0	.	0	.	11	.	0	.	0	.
JMSTF	TF5.5	9	.	0	.	0	.	9	.	0	.	0	.
JMSTF	TF5.5A	8	.	0	.	0	.	8	.	0	.	0	.
JMSTF	TF5.6	9	.	0	.	0	.	9	.	0	.	0	.
JMSTF	TF5.6A	8	.	0	.	0	.	8	.	0	.	0	.
APPTF	TF5.4	6	.	0	.	0	.	6	.	0	.	0	.
JMSOH	LE5.1	7	5.8	15	.	0	.	7	5.5	12	.	0	.
JMSOH	RET5.2	9	.	0	.	0	.	8	4.0	1	.	0	.
CHKOH	RET5.1	2	.	0	.	0	.	2	.	0	.	0	.
CHKOH	RET5.1A	3	.	0	.	0	.	3	.	0	.	0	.
JMSMH	LE5.2	9	6.0	40	.	0	.	8	6.0	31	8.0	1	2.0
JMSMH	LE5.3	7	4.0	22	.	0	.	7	4.0	19	.	0	.
JMSPH	LE5.4	15	8.0	29	13.0	3	7.3	15	12.0	10	10.0	1	4.0
JMSPH	LE5.5	22	6.5	72	12.5	58	4.0	20	8.5	53	13.5	37	4.0
WBEMH	WBE1	5	3.0	6	.	0	.	4	2.5	3	.	0	.
SBEMH	SBA1	13	6.5	33	.	0	.	13	5.0	67	7.0	67	2.0
SBEMH	SBC1	12	3.5	67	6.5	33	3.0	12	5.0	67	.	0	.
SBEMH	SBD1	12	4.5	67	.	0	.	12	4.0	67	6.5	33	2.0
SBEMH	SBD4	3	.	0	.	0	.	3	.	0	.	0	.
SBEMH	SBE2	13	5.5	61	9.0	36	3.5	13	3.5	31	9.5	16	6.0

Exhibit D-3: Median Station Pycnocline Depths and Percent Occurrence: 1985–2000

		Spring (March–May)						Summer (July–September)					
Segment	Station	Station Depth	Upper Depth	Pct Upper	Lower Depth	Pct Lower	Interpyc Depth	Station Depth	Upper Depth	Pct Upper	Lower Depth	Pct Lower	Interpyc Depth
SBEMH	SBE5	10	4.5	70	6.5	18	2.0	10	4.5	44	6.5	3	3.0
EBEMH	EBE1	9	6.5	48	7.5	15	2.0	8	4.5	25	7.3	9	2.8
ELIMH	ELI2	14	7.5	76	11.5	42	3.0	14	7.5	34	9.5	16	3.0
LAFMH	LAF1	6	2.5	17	.	0	.	5	.	0	.	0	.
ELIPH	LE5.6	15	8.0	43	12.0	10	4.0	15	12.0	21	14.0	4	2.0